Unit 6 – Induction Motor Drives

Syllabus

- Speed control methods
  - ✓ Variable voltage control
  - ✓ Constant V/f control or Variable frequency control
  - ✓ Rotor resistance control
  - ✓ Slip power recovery
- Voltage source inverter fed drives
- Current source inverter fed drives
- Braking

References

1. Rashid. M. H., “ Power Electronics – circuits, Devices and Applications”, Prentice Hall India, New Delhi, 2013.

2. Gopal K. Dubey, “Fundamentals of Electrical Drives”, Narosa Publications, 2nd edition, 2002.

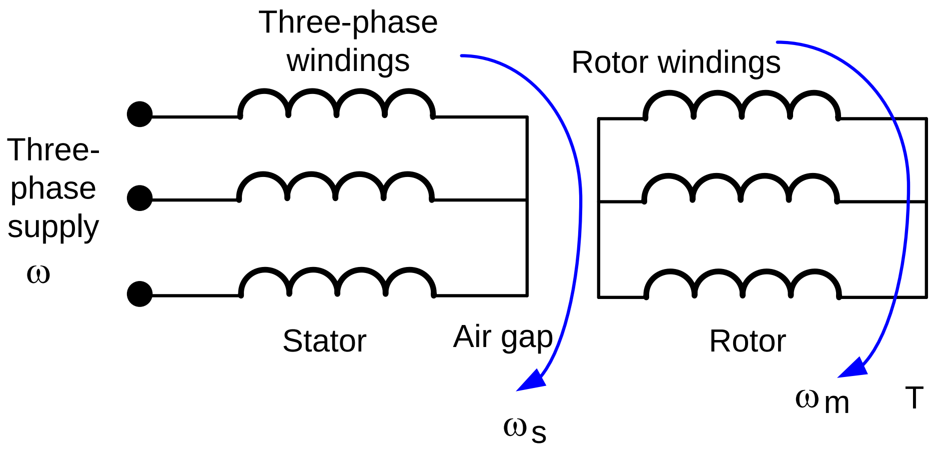
Why induction motor (IM)?

- Robust; No brushes. No contacts on rotor shaft
- High Power/Weight, Lower Cost/Power ratios
- Easy to manufacture
- Almost maintenance-free, except for bearing and other “external” mechanical parts

Applications

- Conveyer line (belt) drives
- Paper mills
- Electric traction,
- Elevators,
- Air-conditioning

Three-phase induction motor

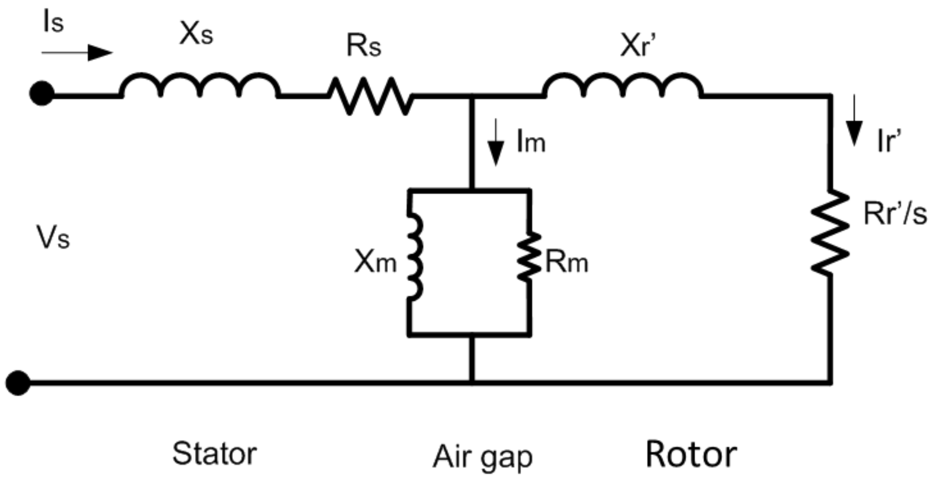


- **Stator**
- **Rotor**
- **Air gap**

The speed of rotation of field is called the **synchronous speed** ω_s , which is defined by :

$$\omega_s = \frac{2\omega}{p} \quad \text{or} \quad N_s = \frac{120f}{p}$$

- A three phase supply is give to the stator
- Due to interaction of flux produced by the three phase current flowing through the stator, RMF at synchronous speed is produced
- As a result, EMF is induced in the rotor bars (for squirrel cage) and current will be flowing in the rotor conductors.
- Conductor placed in a magnetic field will experience a force.
- As per Lenz's law the rotor will rotate in the direction of Rotating Magnetic Field to oppose the effect.
- This causes the motor to rotate.



Equivalent Circuit

The rotor speed or motor speed is : $\omega_m = \omega_s(1-s)$ or $N_m = N_s(1-s)$

Where 's' is slip, as defined as $s = \dfrac{\omega_s - \omega_m}{\omega_s}$ or $s = \dfrac{N_s - N_m}{N_s}$

Torque developed, $T = \dfrac{3}{\omega_{ms}} \times \dfrac{V_s^2 R_r^{'} / s}{\left(R_s + \dfrac{R_r^{'}}{s}\right)^2 + \left(X_s + X_r^{'}\right)^2}$

Rotor Current, $I_r^{'} = \dfrac{V}{\left(R_s + \dfrac{R_r^{'}}{s}\right) + j\left(X_s + X_r^{'}\right)}$

Where :

Rs is resistance per-phase of stator winding

Rr is resistance per-phase of rotor winding

Xs is leakage reactance per-phase of the winding stator

Xs is leakage reactance per-phase of the winding rotor

X_m is magnetizing reactance

R_m is Core losses as a reactance

ω_s is syncronous speed [rad/sec]

ω_m is motor speed [rad/sec]

ω_{ms} is motor supply angular frequency [rad/sec]

N_s is syncronous speed [rpm]

N_m is motor speed [rpm]

p is numbers of poles

ω is the supply frequency [rad/sec]

f is the supply frequency [Hz]

Why Speed Control?

1. **Controlled Starting Current --** When an AC motor is started "across the line," it takes as much as seven-to-eight times the motor full-load current to start the motor and load. This current in the motor windings and generates heat, which will, over time, reduce the life of the motor.

2. **Controlled Acceleration and stopping --** An Adjustable Speed AC Drive starts at zero speed and accelerates smoothly. On the other hand, an AC motor started across the line causes mechanical shock both for the motor and connected load. This shock will, over time, increase the wear and tear on the connected load, as well as the AC motor.

3. **Adjustable Torque Limit --** With an AC motor connected, the motor will continue to try to rotate until the motor's overload device opens (due to the excessive current being drawn as a result of the heavy load). An Adjustable speed AC Drive, on the other hand, can be set to limit the amount of torque so the AC motor never exceeds this limit.

4. **Energy Savings --** Centrifugal fan and pump loads operated with an Adjustable Speed AC Drive reduces energy consumption. Centrifugal fans and pumps follow a variable torque load profile, which has horsepower proportional to the cube of speed and torque varying proportional to the square of speed. As such, if the speed of the fan is cut in half, the horsepower needed to run the fan at load is cut by a factor of eight (1/2)3 = 1/8.

5. **Elimination of Mechanical Drive Components --** Using an Adjustable Speed AC Drive can eliminate the need for expensive mechanical drive components such as gearboxes.

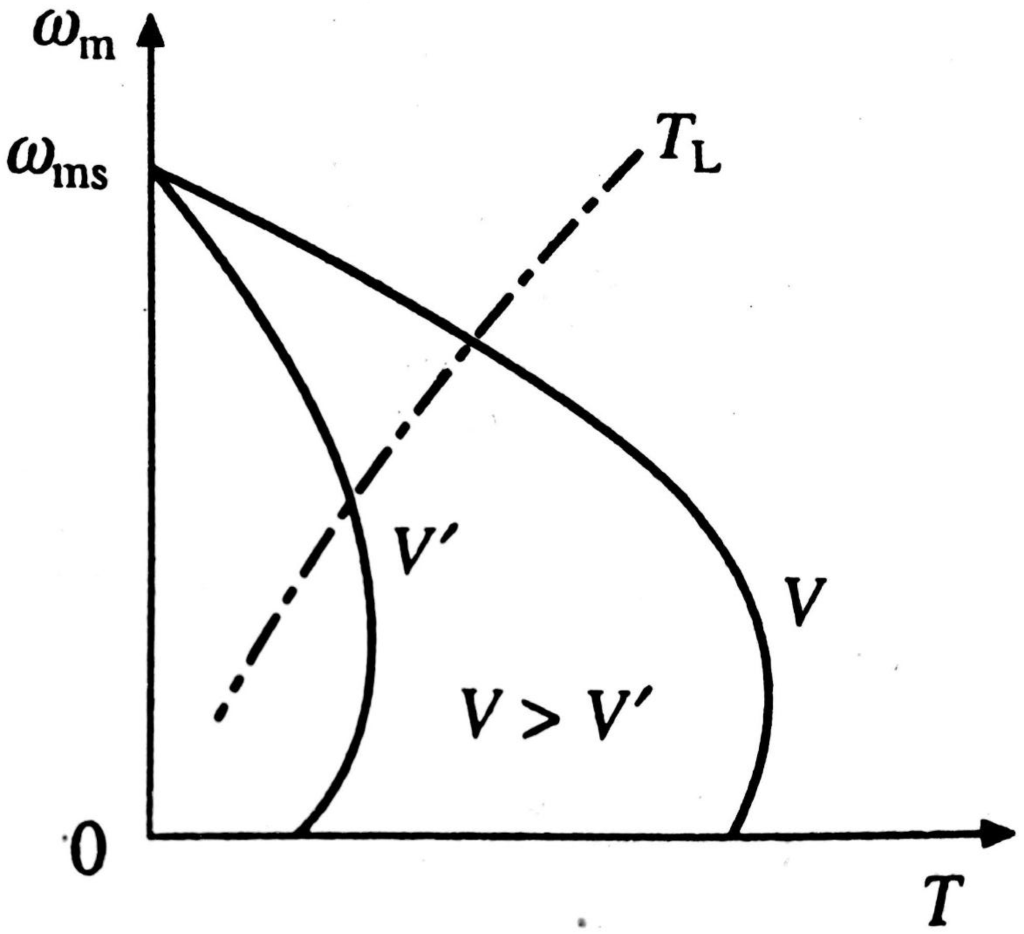
Speed Control of Induction Motor drives

- Speed Control
  - Pole Changing
  - Stator Voltage Control
  - Variable Frequency Control or Constant V/f Control
  - Rotor Resistance Control
  - Slip power Recovery

1. Pole Changing -Applicable to Squirrel cage induction motor
2. Stator Voltage Control -Applicable to both Squirrel cage induction motor and Wound rotor induction motor
3. Variable Frequency Control -Applicable to both Squirrel cage induction motor and Wound rotor induction motor
4. Rotor Resistance Control -Applicable to Wound rotor induction motor
5. Slip power Recovery -Applicable to Wound rotor induction motor

STATOR VOLTAGE CONTROL

- Torque is proportional to stator current which is proportional to the stator voltage. Therefore as the voltage is reduced, speed of the IM also reduces.



- This method is suitable for applications where torque demand reduces with speed e.g., fan and pump drives.
- If stator copper loss, core loss and friction and windage losses are ignored, motor efficiency is given by

$$\eta = \frac{P_m}{P_g} = (1 - s)$$

- The equation shows that the efficiency falls with decrease in speed.
- The speed control is essentially obtained by dissipating a portion of rotor input power in rotor resistance.
- Thus not only the efficiency is low, the power dissipation occurs in the rotor itself, which may overheat the rotor.
- Because of these reasons, this drive is employed in fans, pump drives of low power rating and for narrow speed range.

Problems

A 2.8 kW, 400 V, 50Hz, 4 pole, 1370 rpm, delta connected squirrel-cage induction motor has following parameters referred to the stator: R_s = 2Ω, R_r' = 5Ω, X_s = X_r' = 5Ω, X_m = 80Ω. Motor speed is controlled by stator voltage control. When driving a fan load it runs at rated speed at rated voltage. Calculate motor terminal voltage, current and torque at 1200 rpm.

Solution:

Given: Machine rating: 2.8 kW, 400 V, 50Hz, 4 pole, 1370 rpm, delta connected

Machine parameters: R_s = 2Ω, R_r' = 5Ω, X_s = X_r' = 5Ω, X_m = 80Ω

To Find: Motor terminal voltage, current and torque at 1200 rpm

$$\text{Synchronous speed} = \frac{120f}{P} = \frac{120 \times 50}{4} = 1500\,\text{rpm}$$

$$\text{At full load, Slip, s} = \frac{1500 - 1370}{1500} = 0.0867$$

$$\text{Torque, } T = \frac{3}{\omega_{ms}} \times \frac{V_s^2 R_r' / s}{\left(R_s + \frac{R_r'}{s}\right)^2 + \left(X_s + X_r'\right)^2}$$

$$\text{At full load, } T = \frac{3}{50\pi} \times \frac{400^2 \times 5 / 0.0867}{\left(2 + \frac{5}{0.0867}\right)^2 + (5+5)^2} = 48.13\,\text{Nm}$$

For a fan load torque is proportional to (speed)^2

$$\text{Thus, } T_L = K(1-s)^2$$

$$\text{At full load } T = T_L, \; K(1-0.0867)^2 = 48.13$$

$$K = 57.7$$

$$\text{Hence, } T_L = 57.7(1-s)^2 \qquad (1)$$

$$\text{At 1200 rpm, } \quad \text{Slip}, s = \frac{1500-1200}{1500} = 0.2$$

$$\text{At this speed from equation (1), } T_L = 57.7(1-0.2)^2 = 36.9\,\text{Nm}$$

Since $T = T_L'$, $\boxed{T = 36.9 \text{ Nm}}$

Now

$$\frac{3}{50\pi} \times \frac{V_s^2 \times 5/0.2}{\left(2 + \frac{5}{0.2}\right)^2 + (5+5)^2} = 36.9\,\text{Nm}$$

Which gives, $\boxed{V_s = 253.2 \text{ V}}$

$$I_r' = \frac{V_s}{\left(R_s + \frac{R_r'}{s}\right) + j\left(X_s + X_r'\right)} = \frac{253.2}{\left(2 + \frac{5}{0.2}\right) + j(5+5)}$$

$$= 8.246 - j3.054$$

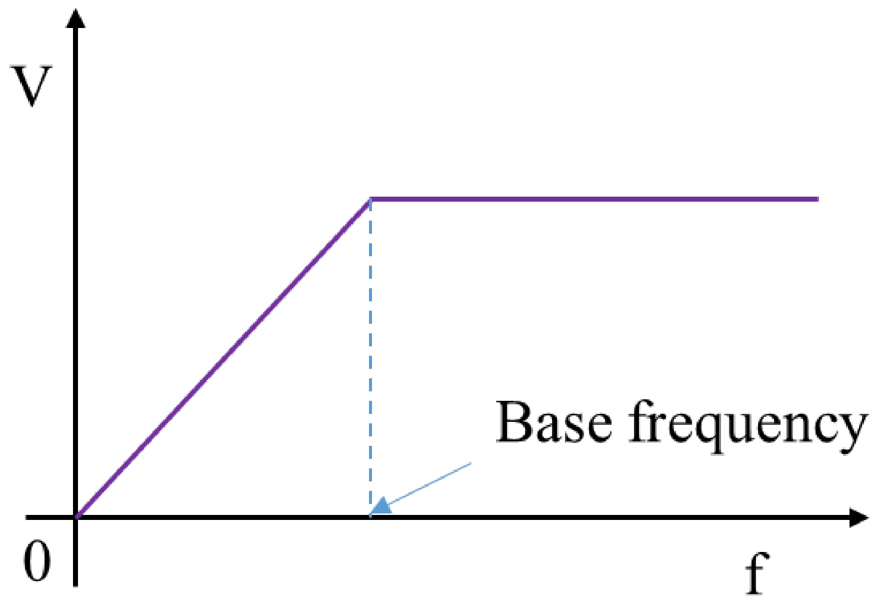
$$I_m = \frac{V_s}{jX_m} = \frac{253.2}{j80} = j3.165$$

$$I_s = I_r' + I_m = 8.246 - j3.054 - j3.165 = 10.328\angle -37^o$$

$$\boxed{\text{Line current} = \sqrt{3} \times 10.328 = 17.89\,\text{A}}$$

CONSTANT V/F CONTROL

- The motor speed can be varied by varying the supply frequency.
- The terminal voltage can be considered proportional to the product of frequency and flux.
- Any reduction in the supply frequency, without any change in the voltage causes an increase in the air gap flux.
- This increase in flux will saturate the motor because induction motors are designed to operate at the knee point of the magnetization characteristics to make the full use of the material.



- Below the base speed, to maintain the air gap flux constant, the terminal voltage is varied with frequency.
- Above the based speed, increase in terminal voltage will cause increase in current leading to more stator copper loss.
- Thus, above base speed, frequency is changed with constant terminal voltage.

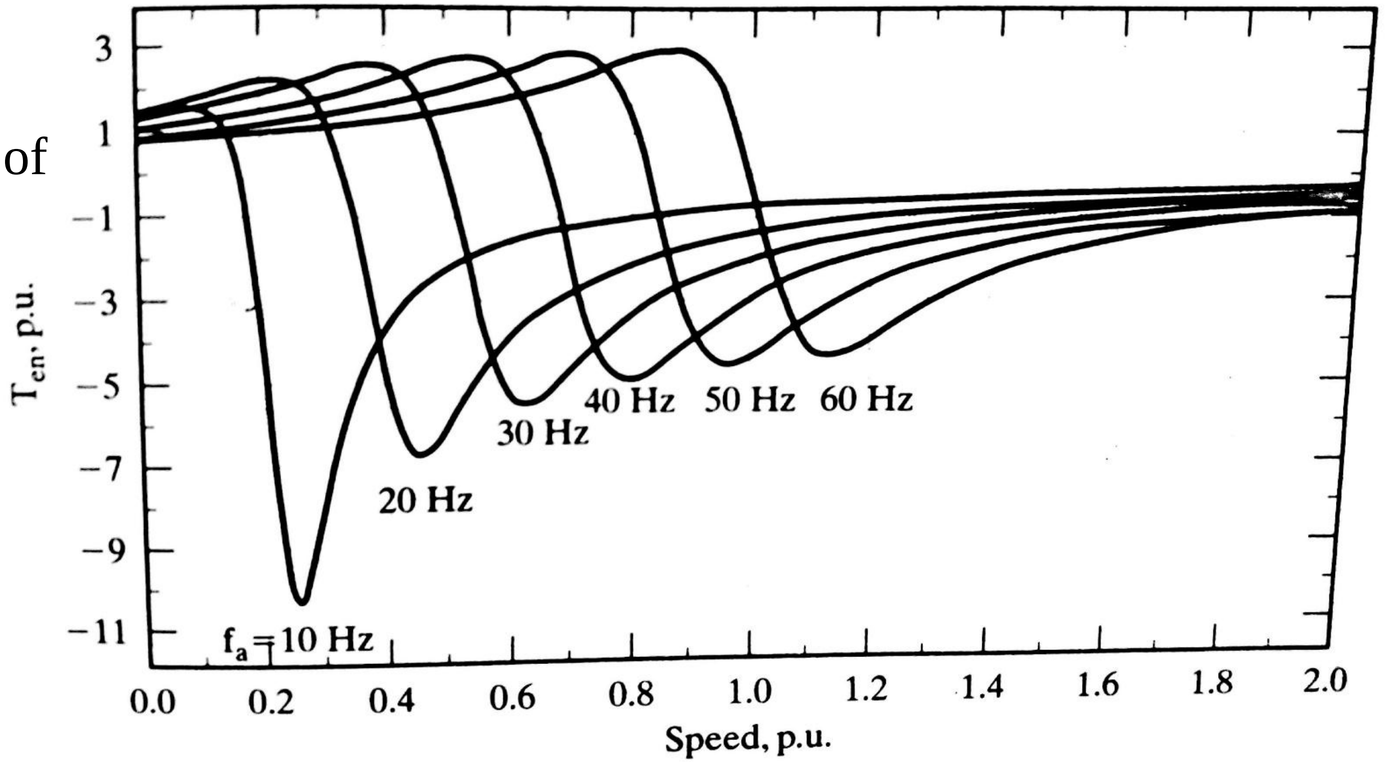
- In constant V/F control., the relationship between the phase voltage and frequency is written as

$$V_{ph} = V_0 + K_{vf} f_s$$

- The relationship between DC link voltage in terms of stator frequency is given by,

$$V_{dc} = 2.22(V_0 + K_{vf} f_s)$$

Where, K_{vf} – Constant
V_0 – Stator resistance drop = $I_s R_s$
I_s – rated stator current
R_s – Stator resistance in Ω



- The major advantage of variable frequency control or constant V/F control is good running and transient performance

Problems

For an induction motor with parameters, 2 hp, 400V, 60 Hz, 3 phase, star connected, 4 pole, 0.72 pf, 0.8 efficiency, Rs = 3 Ω, Rr = 4.1 Ω, X_m = 122.145 Ω, X_{ls} = 6.748 Ω, X_{lr} = 10.29 Ω.

Find the relationship between the DC-link voltage and the stator frequency for the closed loop implementation of a volts/Hz inverter fed induction motor drive.

Solution:

Given: 2 hp, 400V, 60 Hz, 3 phase, star connected, 4 pole, 0.72 pf, 0.8 efficiency, Rs = 3 Ω, Rr = 4.1 Ω, X_m = 122.145 Ω, X_{ls} = 6.748 Ω, X_{lr} = 10.29 Ω.

To Find: The relationship between the DC link voltage and the stator frequency for the closed loop V/F control

The constants required for the implementation of the closed loop drive are: $K_{vf,}$ V_o

$$\text{Maximum slip speed} \cong \frac{R_r}{(L_{lr}+L_{ls})} \cong \frac{4.1}{(10.29+6.748)/377.0} = 91.72\,\text{rad/s}$$

$$\text{Stator Resistive Drop}, V_o = I_{s1}R_s$$

Where I_{s1} – rated stator phase current = $\dfrac{hp \times 745.6}{3V_{ph} \times pf \times efficiency} = \dfrac{2 \times 745.6}{3 \times \left(\dfrac{400}{\sqrt{3}}\right) \times 0.72 \times 0.8} = 3.737\,A$

Hence, $V_o = 3.737 \times 3 = 11.211\ V$

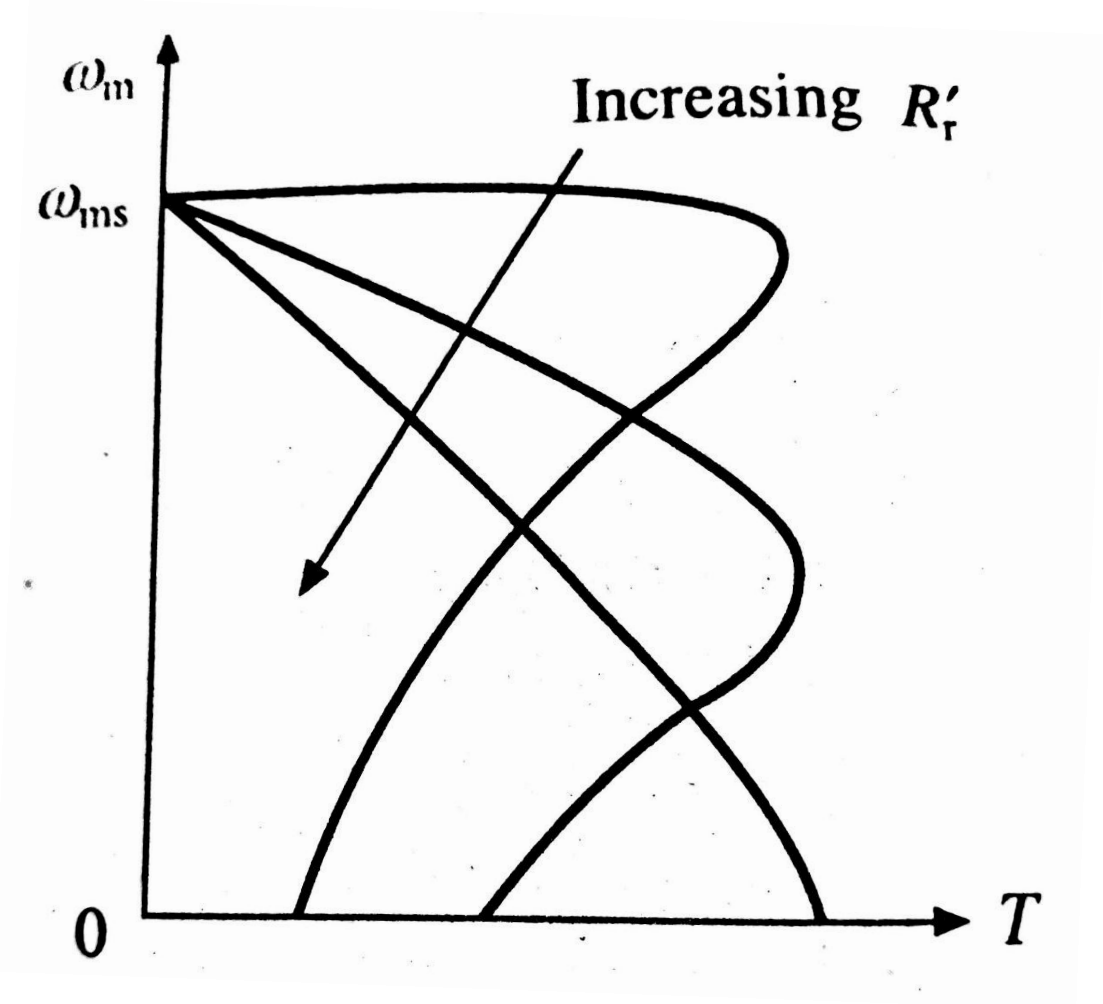
$$K_{vf} = \frac{(V_{ph} - V_o)}{f_s} = \frac{\left(\dfrac{400}{\sqrt{3}} - 11.211\right)}{60} = 3.662\ V/Hz$$

The DC link voltage in terms of the stator frequency is given by,

$$V_{dc} = 2.22\left\{V_o + K_{vf} f_s\right\} = 2.22\left\{11.211 + 3.662 f_s\right\} = (24.89 + 8.125 f_s)\ V$$

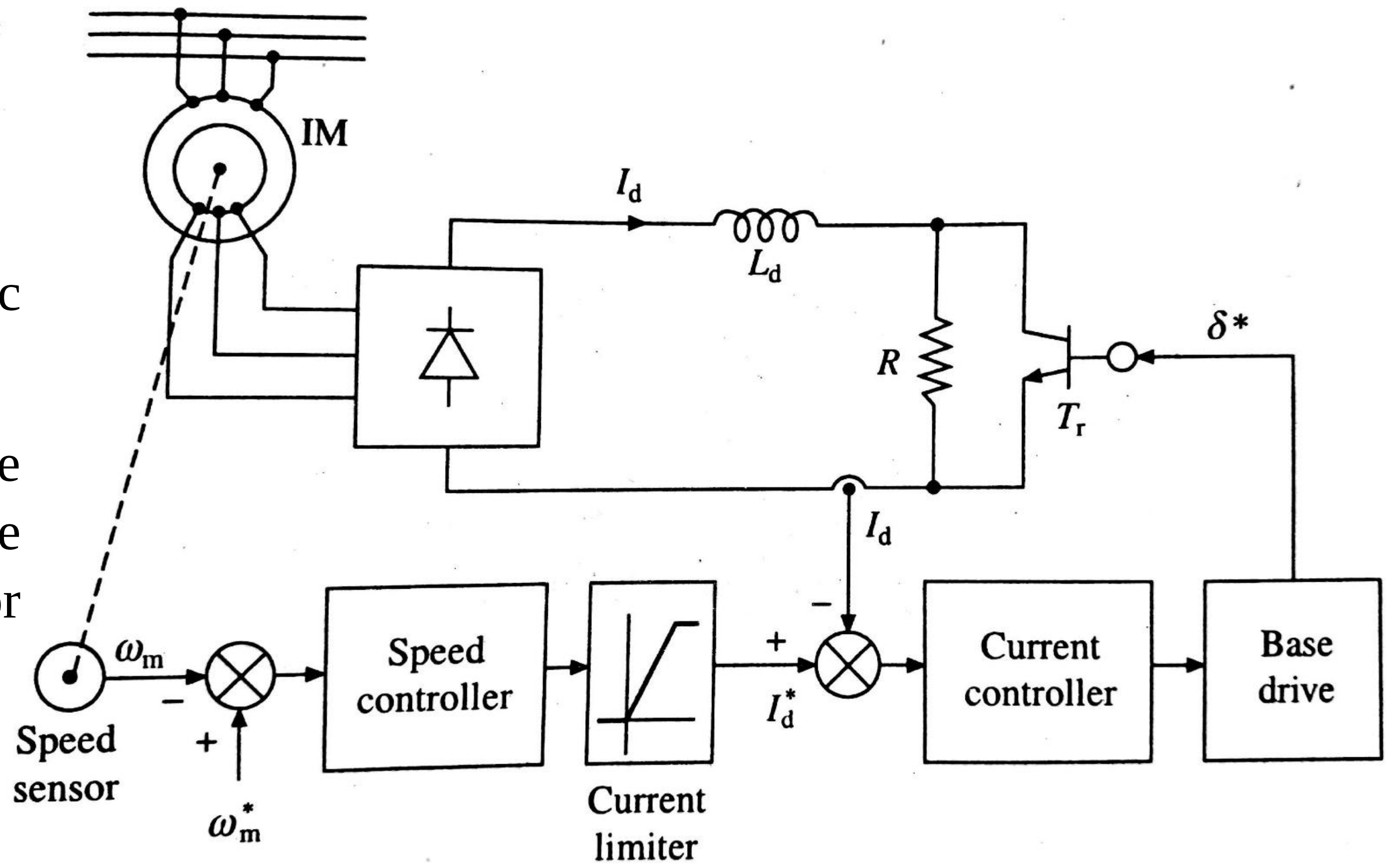
ROTOR RESISTANCE CONTROL

- Speed at which the maximum torque is produced changes with rotor resistance.
- For the same torque, speed falls with an increase in rotor resistance.
- Similar to variable frequency control, motor torque capability remains unaltered even at low speeds.
- Major disadvantages is low efficiency due to the additional losses in resistor connected in the rotor circuit.
- Conventionally rotor resistance control can be implemented using rotary switches, contactors and resistors divided in steps.



➢ For stepless rotor resistance control, static rotor resistance control is employed.

➢ Effective resistance value of the resistance R, is varied by varying the duty ratio of the transistor, Tr. This in turn reduces rotor circuit resistance.

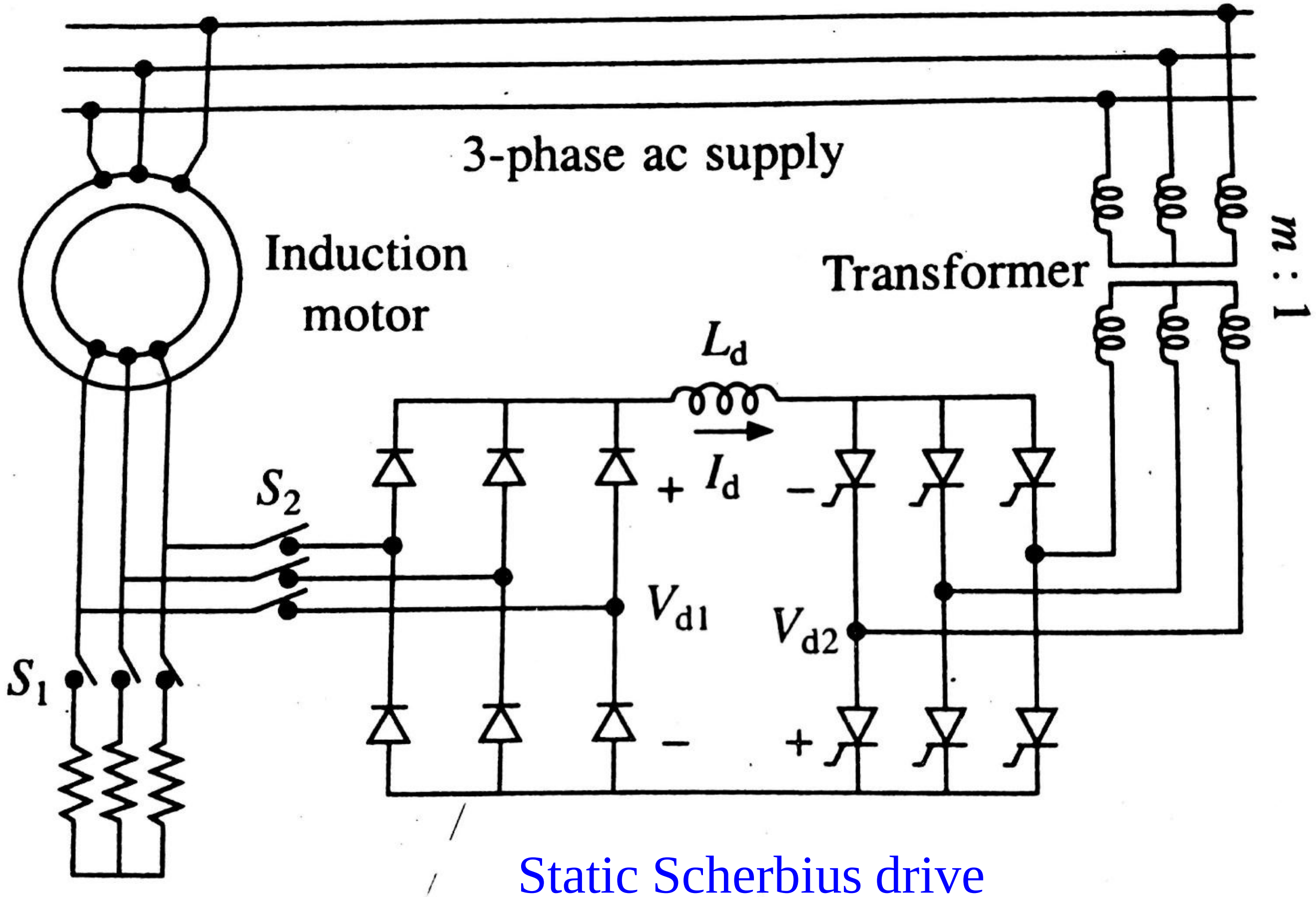


Static Rotor Resistance Control

➢ Compared to the conventional rotor resistance control, static rotor resistance control has several advantages such as smooth and stepless control, fast response, has maintenance, compact in size, simple closed loop control and rotor resistance remains balanced between the three phase for all operating points

SLIP POWER RECOVERY

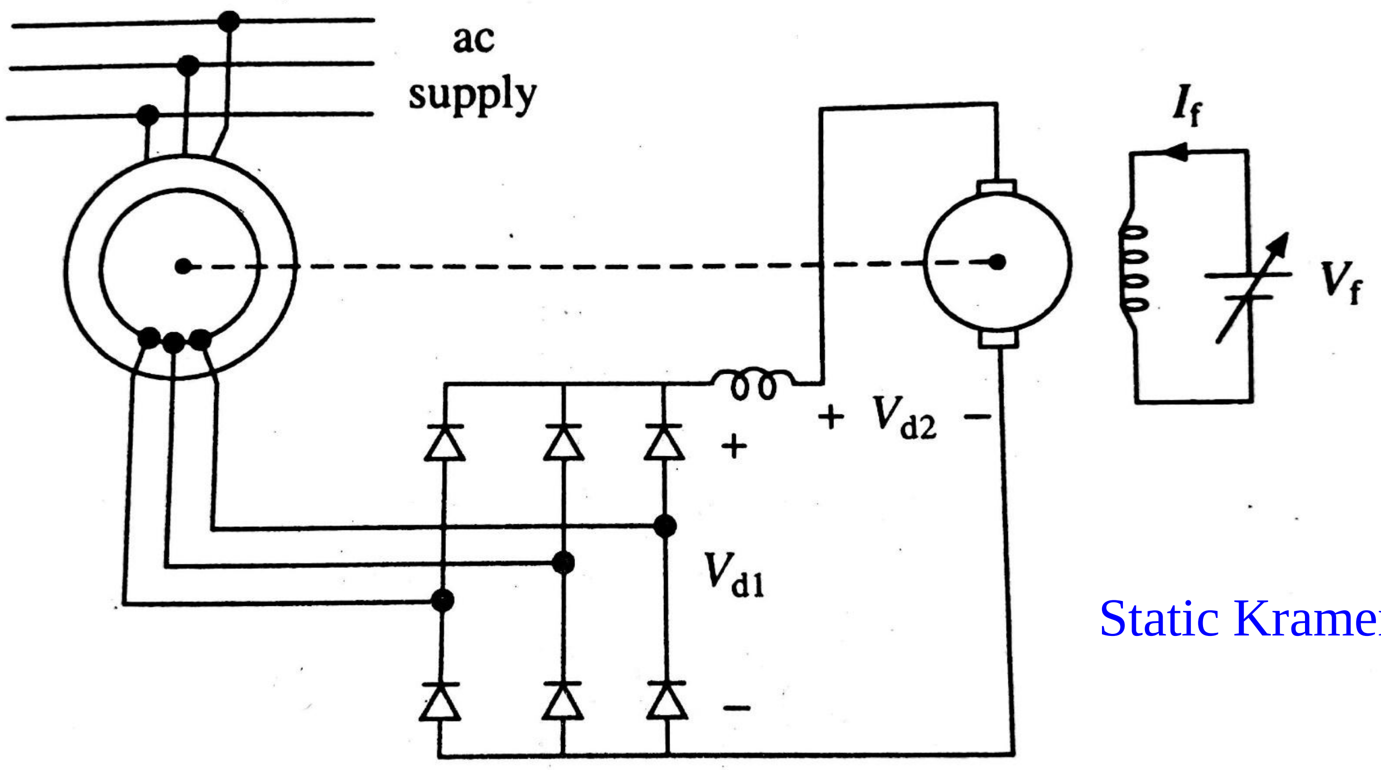
- In slip power recovery scheme, speed control below the slip speed is obtained by controlling the slip power.
- This method is similar to rotor resistance control but, instead of wasting power in external resistors, it is carefully employed here
- Slip power recovery scheme is classified as Static Scherbius drive and Static Kramer drive



Static Scherbius drive

- In Static Scherbius drive, a portion of the rotor AC power is converted into DC by a diode bridge and fed back to the AC source using an inverter.
- Slip power is controlled by controlling inverter firing angle
- This drive provides a constant torque control.

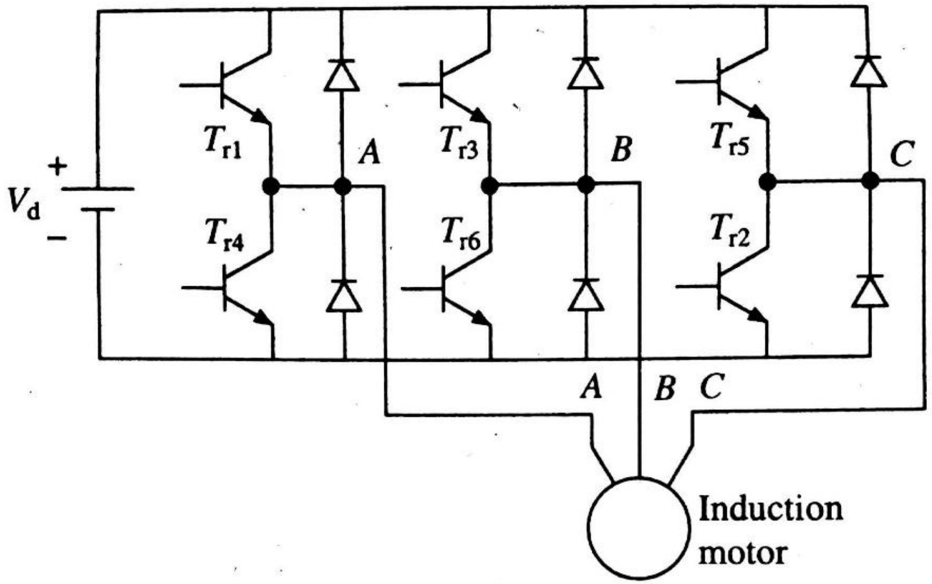
- In static Kramer drive, rotor slip power is converted into DC by a diode bridge. The DC power is now fed to a DC which is mechanically coupled to the IM.
- Speed control is obtained by controlling the field current of the DC motor.
- When larger speed range is required, the diode bridge is replaced by a thyristor bridge. The relationship between V_d and speed can be altered by controlling the firing angle of thyristor bridge

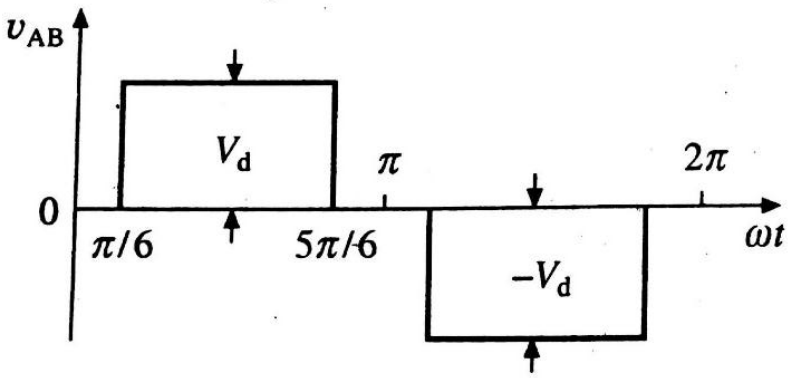


Static Kramer drive

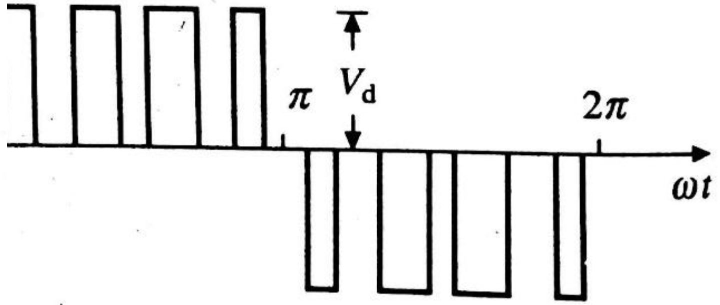
VOLTAGE SOURCE INVERTER (VSI) FED INDUCTION MOTOR DRIVES

- VSI allows a variable frequency supply to be obtained from a DC source.
- VSI can be operated as a stepped wave inverter or a pulse width modulated (PWM) inverter.
- In a stepped wave inverter, transistors are switched in the sequence of their numbers with a time difference of T/6 (60 deg) and each transistor is kept ON for the duration of T/2 (180 deg mode), where T is the time period of one cycle.
- Frequency of inverter operation is varied by varying ‘T’ and the output voltage of the inverter is varied by varying the DC input voltage.



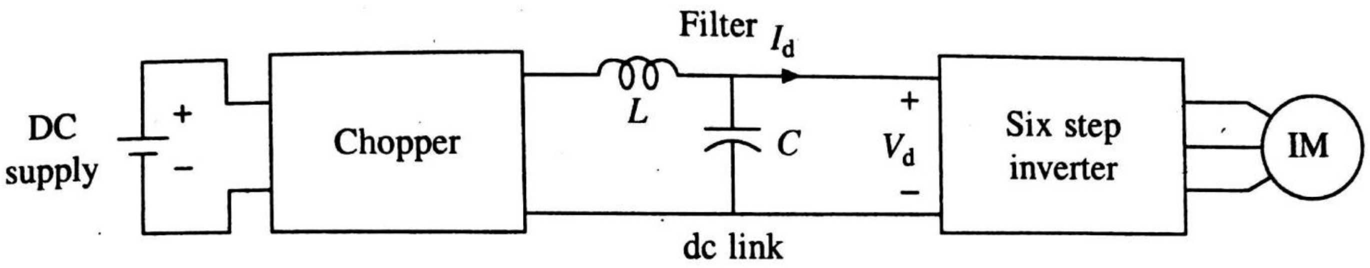


Stepped wave inverter line voltage waveform

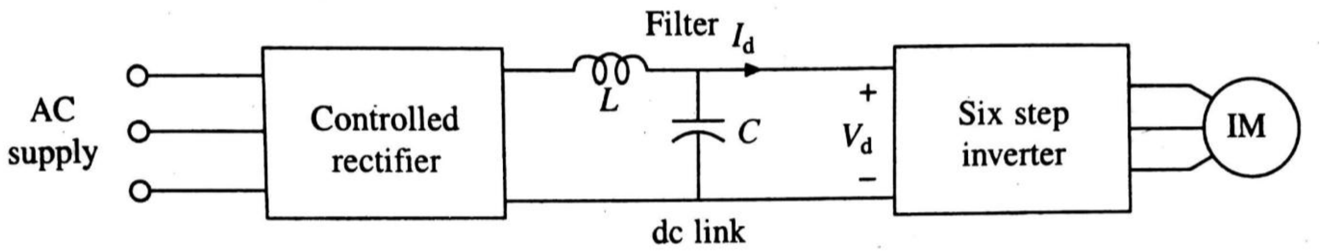


PWM inverter line voltage waveform

- When supply is DC, variable DC input voltage is obtained by connecting a chopper between DC supply and inverter.



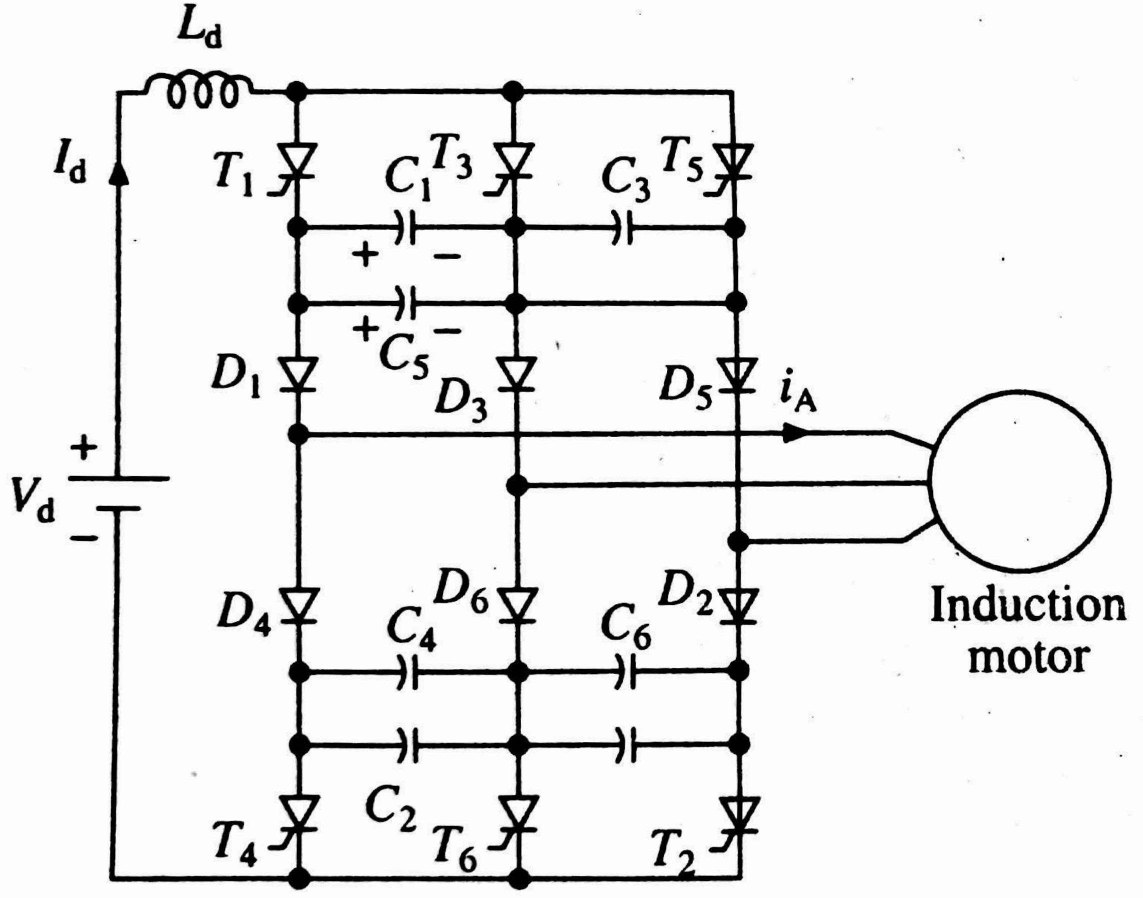
- When supply is AC, variable DC input voltage is obtained by connecting a controlled rectifier between AC supply and inverter.

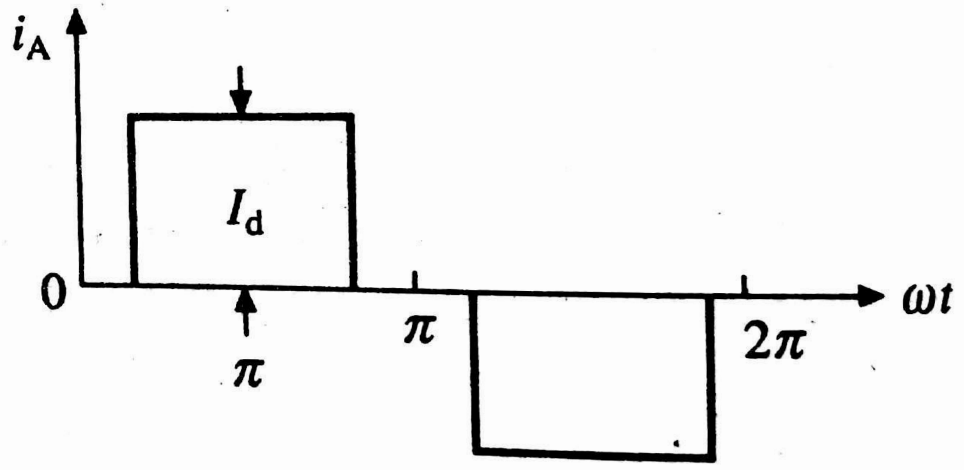


- A large electrolytic filter capacitor is connected in the DC link to make inverter operation independent of rectifier or chopper and to filter out the harmonics in the DC link voltage.
- The main drawback of stepped wave inverter is the large harmonics of low frequency in the output voltage.
- The harmonics in the motor currents produce torque pulsations and derate the motor.
- In PWM inverter, harmonics can be reduced and low frequency harmonics are eliminated. Since, the output voltage can be controlled by PWM, no arrangement is required for the variation of input DC voltage

CURRENT SOURCE INVERTER (CSI) FED INDUCTION MOTOR DRIVES

- The CSI has diodes D1 – D_6 and capacitors C_1-C_6 to provide commutation to thyristors T_1-T_6.
- The thyristors are fired with a phase difference of 60^0 in sequence of their numbers.
- Inverter behaves as a current source due to the presence of large inductance in the DC link.

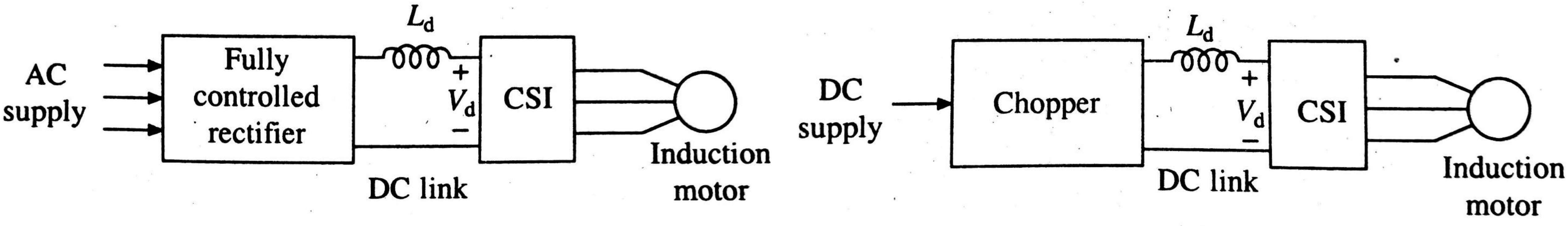




- For a given speed, torque is controlled by varying the DC link current Id by changing the value of input DC voltage, V_d.

- Therefore, when supply is AC., a controlled rectifier is connected between the supply and inverter and when the supply is DC, a chopper is interposed between the supply and inverter.

- The maximum value of DC output voltage of the fully controlled rectifier and chopper are chosen so that the motor terminal voltage saturates at the rated value.



(b)

Comparison of current source inverter (CSI) and voltage source inverter (VSI) fed induction motor drives

- CSI is more reliable than VSI because,
    1. Conduction of two devices in the same leg due to commutation failure does not lead to sharp rise of current through them.
    2. It has inherent protection against a short circuit across motor terminals

- Because of large inductance in the DC link and large capacitors (to reduce ripples in the output) CSI drive has higher cost, weight and volume, lower speed range and slower dynamic response.

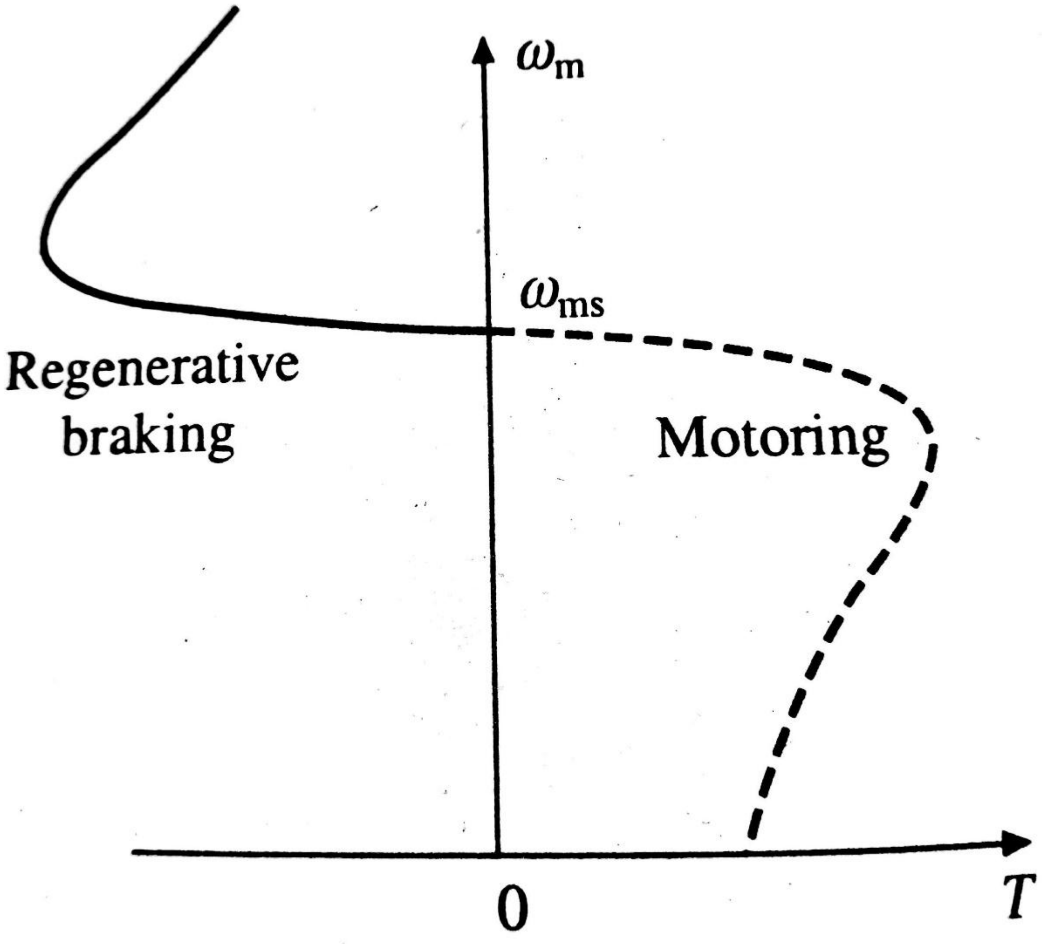
- The CSI drive is not suitable for multi motor drives. Hence each motor is fed from its own inverter and rectifier. A single converter can be used to feed a number of VSI motor systems connected in parallel. A single VSI can similarly feed a number of motors connected in parallel.

Braking of Induction Motor Drives

- A running induction motor can be braked using the following methods,
  - ✓ Regenerative Braking
  - ✓ Plugging or Reverse voltage braking
  - ✓ Dynamic braking
    - AC dynamic braking
    - Self excited braking using capacitors
    - DC dynamic braking
    - Zero sequence braking

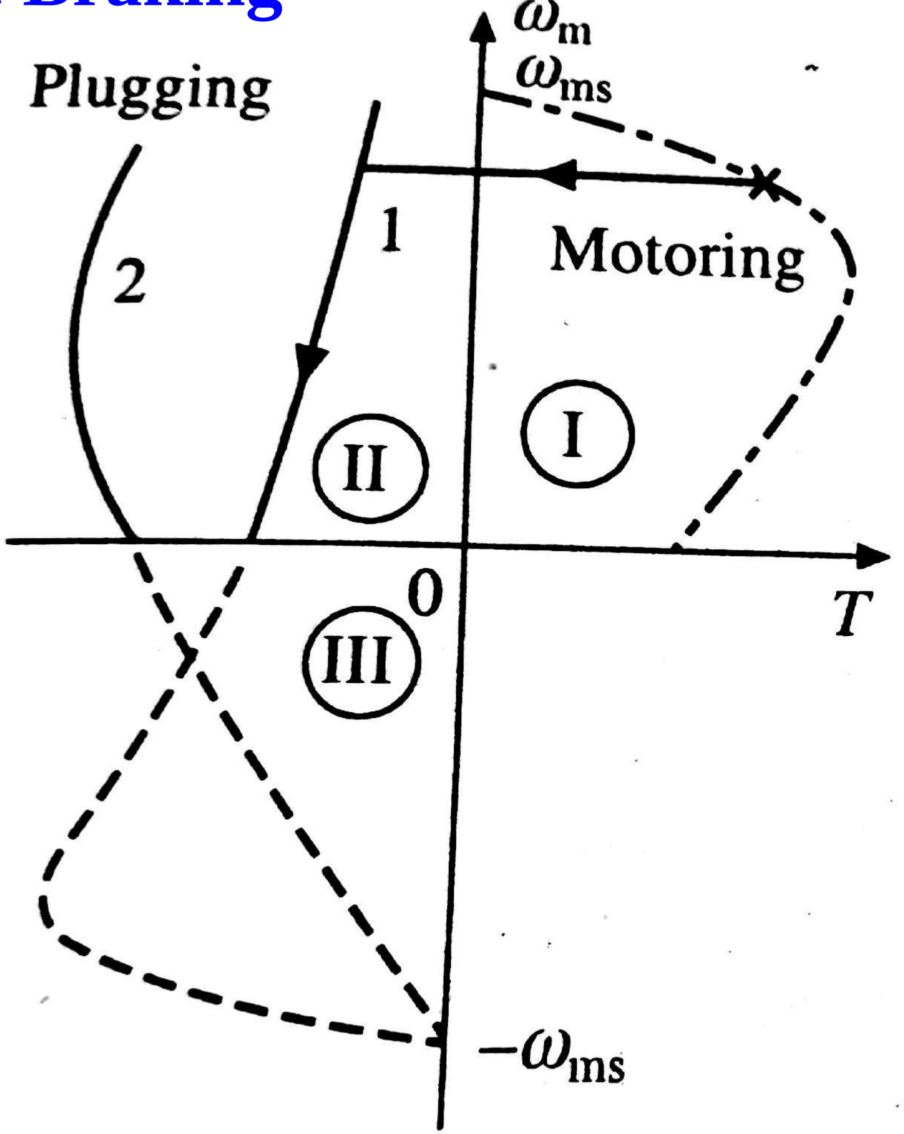
Regenerative Braking

- In regenerative braking, the kinetic energy stored in the motor is utilized to cause braking. The generated energy is stored in battery.
- For an induction motor, if the rotor speed becomes greater than the synchronous speed, relative speed between the rotor conductors and air gap rotating field also reverses.
- This reverses the rotor induced EMF, rotor current and stator current. Thus power flow reverses, giving regenerative braking.
- When the induction motor is fed from constant frequency source, regenerative braking is possible only for speeds greater than synchronous speeds.
- Whereas, with a variable frequency source, it can also be obtained for speeds below synchronous speeds.



Plugging or Reverse Voltage Braking

- By interchanging connections of any two phases of the stator with respect to supply terminals, motoring operation shifts to plugging.
- Plugging characteristics are actually extension of motoring characteristics for negative phase sequence from quadrant 3 to 4.
- Reversal of phase sequence reverses the direction of rotating field.
- The torque is not zero at zero speed. So the motor smoothly decelerates and accelerates in reverse direction.
- This makes it necessary to use an additional device for detecting zero speed and disconnecting motor from the supply.

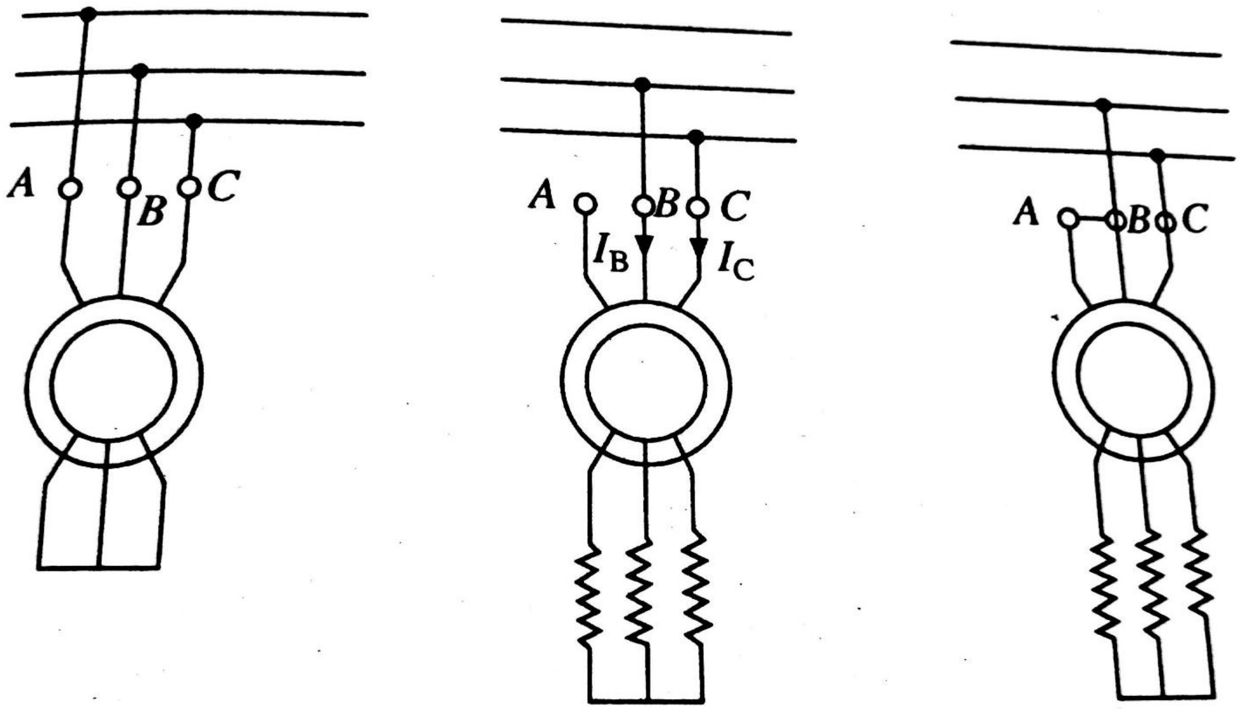


1 : Natural characteristic
2 : With external resistance in rotor

Dynamic or Rheostatic Braking

(a) AC Dynamic Braking

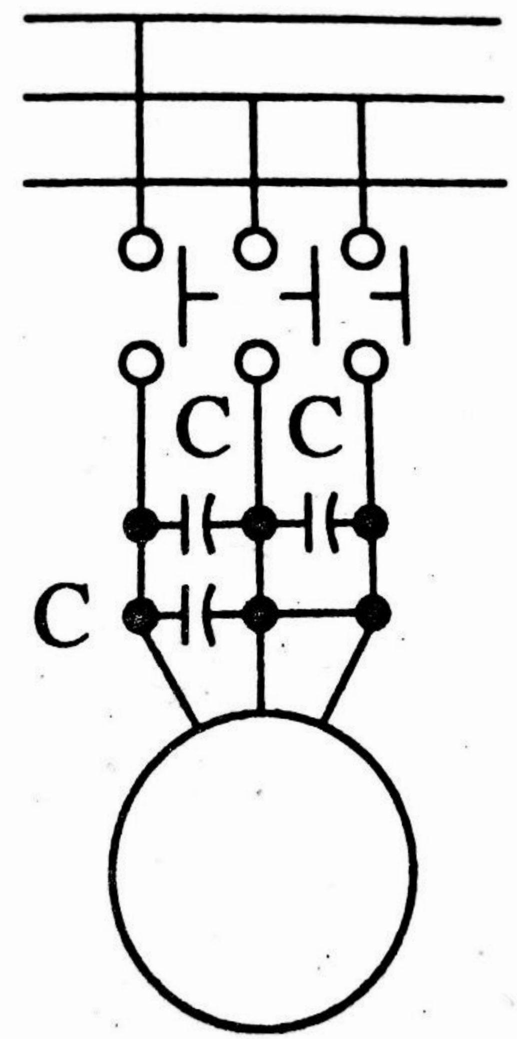
- AC Dynamic braking is obtained when the three phase motor is run from a single phase supply by disconnecting one phase from the source or leaving it open (Fig. b) or connecting to the other machine phase (Fig. c).



(a) Motoring (b) Two lead connection (c) Three lead connection

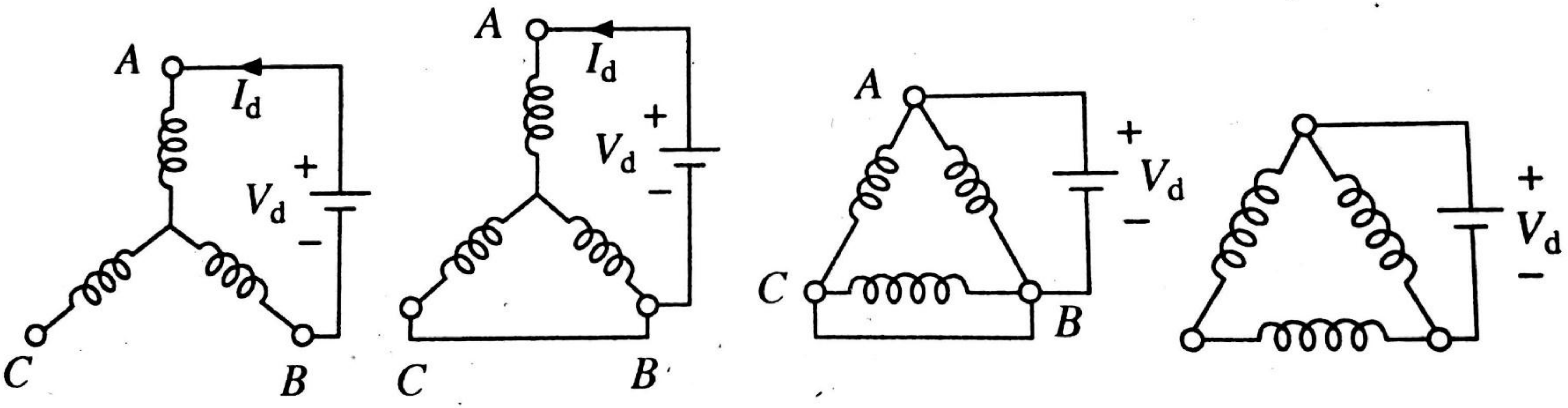
(b) Self-Excited Braking using Capacitors

- For braking, motor is operated as a self-excited Induction Generator (IG) and disconnected from power supply.
- The reactive power is fed to the IG by the three capacitors connected permanently across the motor terminals.
- The reduction in speed, reduces the magnetization. At certain critical speeds, machine does not self-excite, braking torque reduces to zero.
- External resistors may also be connected across stator terminals to increase braking torque.



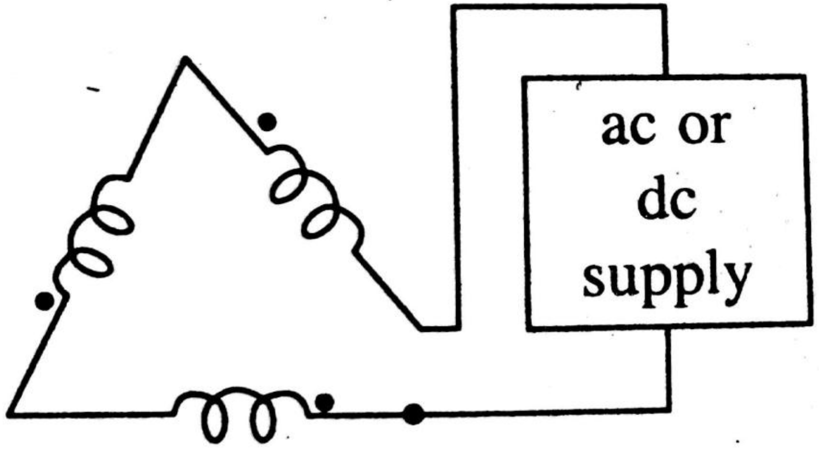
(c) DC Dynamic Braking

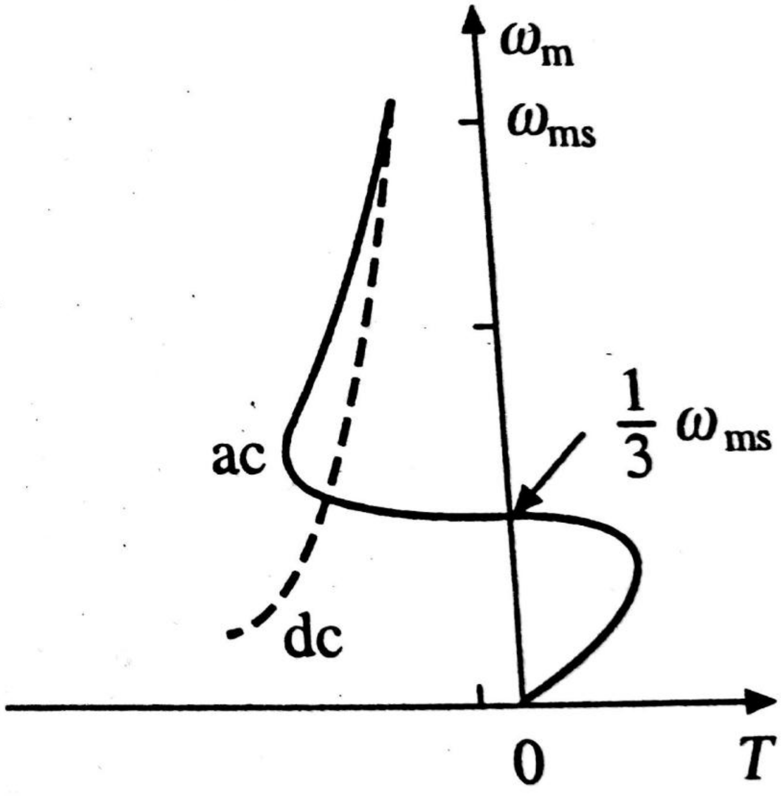
- It is obtained when the stator of an induction motor running at a speed is connected to a DC supply.



(d) **Zero Sequence Braking**

- In this braking, the three stator phases are connected in series across either a single phase AC or a DC source.





Thank You